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TITLE THE TITAN REVERSED-FIELD PINCH REACTOR: DESIGN-POINT DETERMINATION AND PARAMETRIC

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THE TITAN REVERSED-FIELD PINCH REACTOR: DESIGN-POINT DETERMINATION AND PARAMETRIC STUDIES†

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Abstract: The multi-institutional TITAN study has examined the physics, technology, safety, and economics issues associated with the operation of a Reversed-Field Pinch (RFP) magnetic fusion reactor at high power density. A comprehensive system and trade study has been conducted as an integral and ongoing part of the reactor assessment. Attractive design points emerging from these parametric studies are subjected to more detailed analysis and design integration, the results of which are used to refine the parametric systems model. The design points and tradeoffs for two TITAN/RFP reactor embodiments are discussed.

1. INTRODUCTION

The Reversed-Field Pinch (RFP) is a toroidal, axisymmetric magnetic-confinement approach characterized by high beta and amenable to operation at high power density. A multi-institutional study (TITAN)[1,2] has explored the potential of this approach in terms of physics (e.g., start-up, transport, equilibrium/stability, current drive, impurity control), engineering (e.g., neutronics, heat removal, coil design, maintenance), economics (e.g., cost of electricity), and safety and environmental (e.g., accident control and rad-waste) issues. As a part of this study, the operating space, key tradeoffs, and crucial sensitivities are examined using a comprehensive systems model to provide guidance that reflects the evolving state of knowledge in the physics of RFP confinement, current drive, and impurity control. Representative design points are identified that highlight the key physics features of the RFP and embody the several engineering approaches selected for detailed consideration by the TITAN team. Preliminary identifications[1,3] of TITAN design points are extended and superceded by this effort. Trade and sensitivity studies establish the context of the design and characterize a "design window" of attractive RFP reactor operation. After giving a brief background in Sec. 2 and describing the systems model and basecase assumptions in Sec. 3., main results are given in Sec. 4. The summary and conclusions are given in Sec. 5.

2. BACKGROUND

An RFP plasma is confined by a combination of a poloidal field, B_θ, generated by a toroidal current, I_ϕ, flowing in the plasma,

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and a toroidal field, B_ϕ, produced partly by currents flowing in the plasma and partly by external coils. The distinguishing features of the RFP are: (a) $B_\theta \simeq |B_\phi|$ within the plasma, and (b) the toroidal field is reversed and much smaller in magnitude in the outer region with respect to the value on the axis. The safety factor, $q = r_p B_\phi / R_T B_\theta$, where the minor and major radii of the plasma are r_p and R_T, respectively, is less than unity, creating the possibility of large plasma current density, strong ohmic heating, low magnetic fields at coils, and a close coupling of poloidal and toroidal circuits through the plasma to allow oscillating-field current drive (OFCD)[4-6] for steady-state sustainment. A fundamental property of the RFP is a field configuration in a near-minimum-energy state to which the plasma relaxes;[7] the generation of the reversed toroidal field is a natural consequence of this relaxation process. Typical RFP poloidal beta values, β_θ, equal or exceed 0.20, allowing high plasma DT-fusion power densities ($\sim$70 MW/m^3). Energy confinement scales as $\tau_E \propto I_\phi^\nu r_p^2$, where $\nu \simeq 1.0$. These physics characteristics lead to a high-power-density, potentially steady-state plasma configuration that externally is dominated by relatively weak poloidal fields; the promise for an improved commercial reactor results.

After an initial period of examining a wide range of blanket/shield configurations, two main engineering design options have emerged from the TITAN project and are considered in detail: (TITAN-I) a Li/Li/V (breeder/coolant/structure) loop configuration and (TITAN-II) a $LiNO_3/H_2O$/HT-9 configuration immersed in a water pool. The first option incorporates the Integrated Blanket Shield (IBC) concept,[8] wherein the toroidal magnetic field is produced by currents conducted in the Li breeder/coolant, with Joule losses being recovered directly in the thermal cycle. The second options relies on low-field copper-alloy toroidal-field and divertor coils. Both options assume steady-state operation with OFCD and toroidal-field-divertor impurity control and operate at aggressive first-wall neutron loadings ($\sim$18 MW/m^2) to reduce the physics size of the fusion power core (FPC); factory fabrication and efficient integrated testing/maintenance of the FPC result together with cost savings and high operational availability and improved performance in terms of the mass-power-density (MPD kWe/tonne) and cost-of-electricity (COE, mills/kWeh) figures of merit.

3. MODEL

A parametric systems model has been developed[9,10] and refined[1,3] for the present application using COE as an object function. The basic FPC geometry is illustrated in Fig. 1. A moderate aspect ratio ($A = R_T/r_p$) plasma is surrounded by an engineering structure beginning at the first-wall radius, r_w. A conventional design fits a blanket/reflector/shield annulus around the first wall followed by a resistive normal-conducting copper-alloy toroidal-field (TF) coil set and a dominant resistive coil ohmic-heating (OH) coil set. A separate equilibrium-field (EF) coil set could be either superconducting (SC) or normal conducting (NC), the former option requiring additional local shielding.

The IBC features incorporated in the TITAN-I option combine the TF-coil annulus with the blanket. Scaling relationships for OFCD systems,[6] magnetic divertor impurity control,[10,11] and blanket thermalhydraulics[12] are incorporated into the systems model. Unit cost factors (i.e., \$/kg, \$/m^3, \$/W, etc.) for key FPC components and other reactor subsystems are consistent with modern US fusion reactor design practice.[13]

The systems code incorporates a series of computational search loops that vary coil properties (dimensional, coil filling fraction, current density, etc.) and plasma characteristics (major and minor radii, temperature, ignition $n\tau_E$, etc.) used to identify minimum-COE solutions for a range of fixed (and subsequently varied) physics, engineering, economic, and operational parameters. Typically, results are displayed at the last level of this total optimization procedure, this final level being the minor plasma radius, r_p, to illustrate the intrinsic sensitivity rather than presenting a single, optimized design point. Specific parameters of TITAN/RFP design points appropriate to these overall configurational options are selected, coordinated, and optimized by means of parametric systems design code, incorporating models of key FPC and plant subsystems and monitoring COE. Typically, net electric power output is ~1,000 MWe in an optimized device with major toroidal radius $R_T = 3.9$ m, minor plasma radius $r_p = 0.6$ m, and plasma current $I_\phi \simeq 18$ MA. Design points identified by this procedure are subjected to more detailed analysis and subsystem design, with conceptual design results being fed back to the systems design code throughout the project for further optimization and refinement. The systems code, therefore, becomes an active tool in the conceptual engineering design processes, with refinements emerging from the latter process being used in a more advanced systems model to assure a design that is nearer an optimum.

4. RESULTS

Table I lists key design variables that were either fixed or varied in the TITAN/RFP study. The variation of cost with plasma aspect ratio, A R_T/r_p, is weak in the range examined (A 5-9). Establishing a maximum grid power of P_{GRID} 300 MWe delivered to the OH coils in the back-bias mode during startup, and maintaining the peak von Mises stresses in the OH coils below $\sim$200 MPa sets a limit of $A \leq$ 5.5-6; a baseline value of $A = 6.5$ was selected to allow for added startup flux as the conceptual engineering design of the FPC evolved.

Figure 2 illustrates the dependence of COE on plasma radius, r_p, for the indicated fixed parameters for TITAN-I. Curves of constant 14.1-MeV neutron first wall loading, $I_w(MW/m^2)$, and net electrical power output are also shown. The most prominent feature of Fig. 2 is the shallowness of the COE *versus* r_p (and, hence, neutron wall loading, I_w) minimum, although the compressed COE scale should be noted. Nevertheless, increasing I_w from 5 to 10 MW/m^2 and then to the COE-minimum of 20 MW/m^2 results only in a 3 and 11% reduction, respectively, in COE. Other developmental and operational (i.e., single-piece maintenance) incentives not included in the present costing model can justify the higher-I_w, high-MPD design points that reside closer to the COE minimum. The dependence of COE on net plant capacity shown on Fig. 2 is typical of the nuclear economy of scale. Figure 3 displays COE and MPD as a function of neutron wall loading, I_w. Representative TITAN design points are summarized on Table II together with a NC-EFC option.

5. SUMMARY AND CONCLUSIONS

The TITAN/RFP reactor has been examined over a range of neutron wall loadings and varying utilization of resistive versus superconducting magnets. Recent emphasis has been placed on compact, resistive-coil approaches because of the promise of substantial economic, operational, and development advantages for these physically smaller systems. These improved fusion reactors have an FPC engineering power density in the range 5-15 MWt/m^3 and a mass power density in the range 700-900 kWe/tonne, which represent improvements by factors of 10-30 compared with earlier fusion reactor designs.[15] Because the FPC is a smaller proportion of the total plant cost (typically $\sim$10% compared with 25-30% for earlier designs), the unit direct cost, UDC ($/kWe), is less sensitive to related physics and technology uncertainties; installation and maintenance requirements are also eased. A faster, less costly development path also becomes a possibility. Both physics and technological problems remain to be solved for these higher-power-density systems, however. The designs and the relative sensitivities presented herein serve as a basis for quantitative assessment of the above-described issues in the TITAN study.

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15.

TABLE I. FIXED AND VARIED PARAMETERS FOR TITAN/RFP REACTOR OPTIMIZATION AND SENSITIVITY STUDIES[(a)]

<table>
<tr><th></th><th>TITAN-I</th><th>TITAN-II</th></tr>
<tr><td>First-wall/blanket/shield</td><td>Li/V/HT-9</td><td>$LiNO_3/H_2O$/HT-9</td></tr>
<tr><td>Plasma aspect ratio, $A = R_T/r_p$</td><td colspan="2">[6.5]</td></tr>
<tr><td>Minor plasma radius, $r_p(m)$</td><td colspan="2">[0.60]</td></tr>
<tr><td>Plasma average temperature, $T(keV)$</td><td colspan="2">10.</td></tr>
<tr><td>Poloidal/total beta, β_θ/β</td><td colspan="2">[0.20]/($\beta_\theta/2$)</td></tr>
<tr><td>Lawson parameter, $n\tau_E(10^{20}s/m^3)$ (b)</td><td colspan="2">1.92</td></tr>
<tr><td>Pinch parameter, $\theta = B_\theta(r_p)/\langle B_\phi \rangle$</td><td colspan="2">1.56</td></tr>
<tr><td>Reversal parameter, $F = B_\phi(r_p)/\langle B_\phi \rangle$</td><td colspan="2">-0.10</td></tr>
<tr><td>Thermal-conversion efficiency, η_{TH}</td><td>0.44</td><td>0.35</td></tr>
<tr><td>EFC option</td><td colspan="2">SC or NC</td></tr>
<tr><td>OH, TF, DF, EF coil options</td><td>NC/IBC/IBC/SC</td><td>NC/NC/NC/SC</td></tr>
<tr><td>First-wall/blanket/reflector/shield standoff, $\Delta(m) = \Delta fw + \Delta b + \Delta r + \Delta s$</td><td>0.77</td><td>0.50</td></tr>
<tr><td>EFC shield standoff</td><td colspan="2">[0.0(NC), 0.5(SC)]</td></tr>
<tr><td>Blanket neutron energy multiplication, M_N</td><td>1.20</td><td>1.30</td></tr>
<tr><td>SC coil current density, $j_c(MA/m^2)$ (c)</td><td colspan="2">$(96 - 6B_{\theta c})/[1 + (B_{\theta c}/12)^{1.5}]$</td></tr>
<tr><td>NC current density, $j_c(MA/m^2)$ (d)</td><td colspan="2">≤ 50</td></tr>
<tr><td>Plant factor, p_f (e)</td><td colspan="2">$\lesssim$ 0.76(28 day/FPC scheduled maintenance
60 day/year unscheduled maintenance)</td></tr>
<tr><td>FPC radiation lifetime, $I_w\tau(MWyr/m^2)$</td><td colspan="2">[15.]</td></tr>
<tr><td>Typical FPC unit costs ($/kg, 1986)</td><td></td><td></td></tr>
<tr><td>· First-wall/blanket</td><td>395/250/54</td><td>TBD</td></tr>
<tr><td>· Shield (HT-9)</td><td colspan="2">20.</td></tr>
<tr><td>· NC coil</td><td colspan="2">65.</td></tr>
<tr><td>· SC coil</td><td colspan="2">130.</td></tr>
<tr><td>· Structure (HT-9)</td><td colspan="2">20.</td></tr>
<tr><td>· OFCD power costs ($/kVAR)</td><td colspan="2">[25.0]</td></tr>
</table>

(a) Values in brackets [ ] were varied, with nominal design value being shown.

(b) $n = \sum n_i f_i$, where $f_d = f_t = 0.484$, $f_\alpha = 0.03$, $f_{Fe} = 0.003$; $Z_{eff} = 1.69$.

(c) Ref. 14.

(d) Cost optimization related to cost of power supply versus cost of copper usually set j_c for resistive coils far below this limit, with $j_c \simeq$ 5-10 MA/m^2 being typical.

(e) For a given FPC radiation lifetime very high neutron wall loading cases were penalized by more than one 28 day/FPC change out per annum, thereby decreasing p_f and giving rise to an optimum neutron wall loading in the range 15-20 MW/m^2. For systems that are dominated by large axial (toroidal fields and SC coil) costs, these minimum-cost designs occur at much lower neutron wall loadings (3-4 MW/m^2), leading to much larger FPCs for the same power output.

TABLE II. SUMMARY OF TITAN/RFP REACTOR DESIGNS[a]

	NC-EF Coil	TITAN-I	TITAN II
EF Coil Option	NC	SC	SC
Plasma Parameters			
Plasma volume, $V_p(m^3)$	27.7	27.7	27.7
Plasma current, $I_\phi(MA)$	17.82	17.82	17.84
Toroidal current density, $j_\phi(MA/m^2)$	15.8	15.8	15.8
Plasma ion, electron density, $n_{i,e}(10^{20}/m^3)$	8.94	8.94	8.96
Poloidal field at plasma surface, $B_\theta(T)$	5.94	5.94	5.95
Thermal diffusivity, $\chi_E(m^2/s)$	0.315	0.315	0.315
Fusion power density, $P_F/V_p(MW/m^3)$	83.0	83.2	83.5
Plasma ohmic dissipation, $P_\Omega(MW)$	28.5	28.6	28.6
Poloidal-Field Quantities			
Coil thickness, $\delta_{c\theta}(m)$	0.24	0.27	0.22
Average minor radius, $r_{c\theta}(m)$	1.57	1.56	1.29
Coil field, $B_{c\theta}(T)$	2.27	2.29	2.76
OH coil current density, $j_{c\theta}(MA/m^2)$ [b]	17.8	15.6	18.8
Mass of OH coil set, M_{OHC} (tonne)	309.	341.	228.
EF coil current density, $j_{c\theta}(MA/m^2)$	6.1	19.2[c]	20.4
Mass of EF coil set (tonne)	578.	305.	253.
Poloidal-field stored energy, $W_{B\theta}(GJ)$	1.8	5.2	4.2
OH coil dissipation during back-bias (MW)	284.	170.	228.
Toroidal-Field Quantities			
Coil thickness, $\delta_{c\theta}(m)$	0.017	0.28[d]	0.023
Average minor radius of coil, $r_{c\phi}(m)$	1.44	0.675	1.17
Mass of coil, M_{TFC} (tonne)	18	41	21
Reversed-toroidal field during burn, $-B_{\phi R}(T)$	0.382	0.382	0.382
Magnetic energy stored in coil, $W_{B\theta}(GJ)$	0.74	0.16	0.49
TF coil current density, $j_{c\phi}(MA/m^2)$	28.1	1.65	18.8
Ohmic dissipation during burn, $P_\Omega^{TFC}(MW)$	54.1	27.7	29.5
Mass of divertor coil, M_{DFC} (tonne)	3.1	0.55	3.1
Ohmic dissipation in divertor, $P_\Omega^{DFC}(MW)$	24	125	24

	TITAN-I		TITAN-II
Engineering Summary			
Neutron wall loading, $I_w(MW/m^2)$	18.1	18.1	18.2
Engineering Q-value, $Q_E = 1/\epsilon$	3.94	4.34	5.75
Fusion power, $P_F(MW)$	2,301	2,305	2,313
Total thermal power, $P_{TH}(MW)$	2,741	2,917	2,906
Net electrical power output, $P_E(MWe)$	900	988	840
First-wall minor radius, $r_w(m)$	0.66	0.66	0.66
FPC minor radius, $r_s(m)$	1.70	1.70	1.40
Masses (tonne)			
· first-wall/blanket	41	41	48
· reflector/OH-coil "hot shield"	267.	267.	189
· EF-coil shield	0.	325.	290
· total coil set	908.	645.	505
· FPC mass	1,217.	1,280.	1,033
System power density, $P_{TH}/V_{FPC}(MWt/m^3)$	12.3	13.1	19.2
Mass power density, $MPD(kWe/tonne)$ [(f)]	639.	772.	813
Cost Summary			
Cost of electricity, COE(mills/kWeh)[(e)]	42.1	38.2	40.5
Unit direct cost, UDC($/kWe)	1,619.	1,468.	1,594
Total cost, $TC(M\$)$	2,351.	2,369.	2,160
FPC unit cost ($/kg)	144.	146.	130
Fractions of total direct cost (TOC)			
· reactor plant equipment, RPE/TDC	0.43	0.42	0.46
· fusion power core cost, FPC/TDC[(f)]	0.12	0.13	0.10

(a) All designs are for baseline parameters given in Table I, $A = 6.5$, $R_T = 3.9\ m$, $r_p = 0.60\ m$.

(b) Peak current in back-biased state, decreases by factor of ~2 in forward-bias state, subsequently decays to zero upon initiation of OFCD.

(c) Superconducting magnet.

(d) IBC

(e) Near minimum COE.

(f) Does not include structure.